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FIELD EXPERIMENTS SHOW THAT ACOUSTIC PINGERS REDUCE MARINE MAMMAL BYCATCH IN THE CALIFORNIA DRIFT GILL NET FISHERY

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ABSTRACT

A controlled experiment was carried out in 1996–1997 to determine whether acoustic deterrent devices (pingers) reduce marine mammal bycatch in the California drift gill net fishery for swordfish and sharks. Using Fisher's exact test, bycatch rates with pingers were significantly less for all cetacean species combined ($P < 0.001$) and for all pinniped species combined ($P = 0.003$). For species tested separately with this test, bycatch reduction was statistically significant for short-beaked common dolphins ($P = 0.001$) and California sea lions ($P = 0.02$). Bycatch reduction is not statistically significant for the other species tested separately, but sample sizes and statistical power were low, and bycatch rates were lower in pingered nets for six of the eight other cetacean and pinniped species. A log-linear model relating the mean rate of entanglement to the number of pingers deployed was fit to the data for three groups: short-beaked common dolphins, other cetaceans, and pinnipeds. For a net with 40 pingers, the models predict approximately a 12-fold decrease in entanglement for short-beaked common dolphins, a 4-fold decrease for other cetaceans, and a 3-fold decrease for pinnipeds. No other variables were found that could explain this effect. The pinger experiment ended when regulations were enacted to make pingers mandatory in this fishery.

Key words: bycatch, fishery, pinger, cetacean, dolphin, pinniped, *Delphinus delphis*, *Zalophus californianus*, short-beaked common dolphin, California sea lion.

Acoustic deterrent devices (pingers) reduced the bycatch of harbor porpoise (*Phocoena phocoena*) in bottom-set gill nets during controlled experiments: in the Gulf of Maine (Kraus *et al.* 1997), in the Bay of Fundy (Trippel *et al.* 1999), along the Olympic Peninsula (Gearin *et al.* 2000), and in the North Sea.[2] In all cases

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[2] Larsen, F. 1997. Effekten af akustiske alarmer på bifangst af marsvin i garn. Report number 44-97 (unpublished). Available from the Danish Institute for Fisheries Research, Jægersborgvej 64-66, DK-2800 Kgs. Lyngby, Denmark.

a large (approximately 77%–90%) decrease in harbor porpoise mortality was achieved in short-term experiments. The mechanisms are not well understood (Kraus *et al.* 1997), but in field trials and in captive studies, the sounds produced by pingers appear to be aversive to harbor porpoises (Kastelein *et al.* 1995, 2000; Laake *et al.*;[3] Culik *et al.* 2001). Another pinger experiment was conducted in 1994 on a drift gill net fishery for swordfish along the U.S. east coast whose bycatch included a wide variety of cetaceans. Results of that experiment were somewhat equivocal: in paired tests pingered nets had lower bycatch, but both pingered and unpingered nets in the experiment had higher bycatch than unpingered nets in the rest of the fleet.[4] Prior to these recent successes, the use of active or passive acoustic deterrents showed little or no effect on net entanglement of Dall's porpoises (*Phocoenoides dalli*) (Hatakeyama *et al.* 1994), and there was little optimism in the scientific community that such approaches would work with other species (Dawson 1994, Perrin *et al.* 1994, Jefferson and Curry 1996). The recent success of pingers in reducing harbor porpoise entanglements in bottom set gill nets prompted a re-evaluation of their potential to reduce mortality of other cetacean species in other fisheries.[5] In this paper we describe an experiment to evaluate the effectiveness of pingers to reduce cetacean mortality in the drift gill net fishery for swordfish and sharks along the coasts of California and Oregon.

This drift gill net fishery typically operates 37–370 km offshore from southern California to northern California and, in some years, to Oregon (Fig. 1). The primary season for broadbill swordfish (*Xiphias gladius*) is between 15 August and 31 January, but some vessels fish for sharks (primarily common thresher, *Alopius vulpinas*, and shortfin mako, *Isurus oxyrinchus*) between 15 May and 15 August. There were approximately 130 vessels actively fishing in 1995.[6] Vessels are typically 9–23 m in length, and each vessel fishes at night with one multifilament gill net (stretched mesh size of 43–56 cm) with a maximum length of 1,830 m. Nets are suspended completely below the surface by float lines which were a minimum of 11 m in length. Previous bycatch included a wide assortment of cetacean species (Julian and Beeson 1998) including delphinids (common dolphins, Pacific white-sided dolphins, northern right whale dolphins, Risso's dolphins, pilot whales, bottlenose dolphins, and killer whales), beaked whales (Cuvier's beaked whales, Baird's beaked whales, and *Mesoplodon* spp.), dwarf sperm whales, sperm whales, and humpback whales (see Table 2 for scientific names). Based on the

[3] Laake, J., D. Rugh and L. Baraff. 1998. Observations of harbor porpoise in the vicinity of acoustic alarms on a set gill net. U.S. Department of Commerce, NOAA Technical Memorandum NMFS-AFSC-84 (unpublished). 40 pp. Available from the National Marine Mammal Laboratory, 7600 Sand Point Way NE, Seattle, WA 98115, U.S.A.

[4] DeAlteris, J., E. Williams and K. Castro. 1994. Results of an experiment using acoustic devices to reduce the incidental take of marine mammals in the swordfish drift gillnet fishery in the Northwest Atlantic Ocean. Unpublished report. 10 pp. Available from the University of Rhode Island, Kingston, RI 02881, U.S.A.

[5] Reeves, R. R., R. J. Hofman, G. K. Silber and D. Wilkinson. 1996. Acoustic deterrence of harmful marine mammal-fishery interactions. Proceedings of a workshop held in Seattle, Washington, 20–22 March 1996. U.S. Department of Commerce, NOAA Technical Memorandum NMFS-OPR-10 (unpublished). 70 pp. Available from the NMFS Office of Protected Resources, 1335 East/West Highway, Silver Springs, MD 20910, U.S.A.

[6] Barlow, J., K. A. Forney, P. S. Hill, R. L. Brownell, Jr., J. V. Carretta, D. P. DeMaster, F. Julian, M. S. Lowry, T. Ragen and R. R. Reeves. 1997. U.S. Pacific Marine Mammal Stock Assessments: 1996. NOAA Technical Memorandum NOAA-TM-NMFS-SWFSC-248. 223 pp.

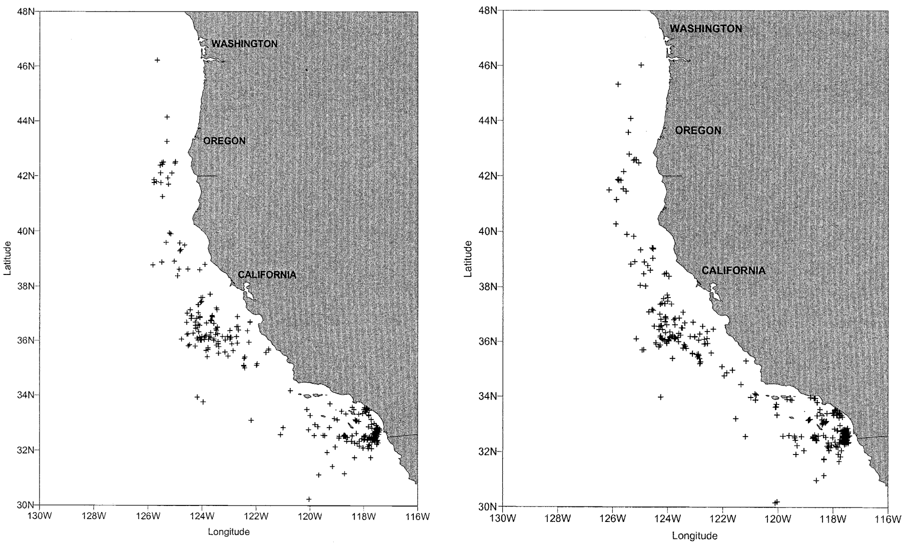

Figure 1. Geographic distribution of sets with pingers (left) and without pingers (right) that were included in analyses.

management scheme used in the United States, the estimated bycatch in 1992–1996 exceeded the PBR (Potential Biological Removal) for some marine mammal species and may not be sustainable.[6] Concern about these bycatch levels prompted the formation of the Pacific Offshore Cetacean Take Reduction Team to identify potential solutions to this problem. The experiment described here was among their first recommendations.

Methods

Experimental Design

The experiment was designed to maximize statistical power and minimize bias. Each set was assigned randomly as either an experimental set (with pingers) or a control set (without pingers). The experiment was carried out only on those 20%–25% of fishing trips that carried National Marine Fisheries Service bycatch observers. Prior to a trip, observers were given packets of 10 sealed and numbered envelopes. Prior to each set, observers would open the envelope with the number corresponding to the sequential set number for that trip and would read a card which would indicate whether that set was to be "experimental" or "control." Randomized within each packet of ten envelopes were five cards labeled "pingers" and five labeled "no pingers." If the number of sets per trip exceeded 10, a new packet of envelopes was used starting with set number 11. To minimize the potential for experimental manipulation, the selection of experimental and control sets was made after the skipper had identified a fishing location and immediately prior to setting the net. A double-blind experimental design (such as that used by Kraus *et al.* 1997 and Larsen[2]) was logistically infeasible.

Dukane NetMark 1000[7] pingers were used during this experiment. These commercially produced pingers emit a tonal signal of 300 msec duration every 4 sec with a fundamental frequency of 10–12 kHz and with significant harmonics up to 100 kHz. The manufacturer cites a source level of 132 dB (re: 1 μPa @ 1 m), but independent calibration studies have shown considerable variation in source levels between 120 and 146 dB ($\bar{X} = 138$ dB, $n = 35$).[8,9] At a source level of 132 dB, these pingers were estimated to be 15 dB above ambient noise levels at 100 m distance in the near-bottom environment in the Gulf of Maine (Kraus *et al.* 1997). Fishermen were instructed to place one pinger at each end of the floatline and at 91 m intervals along the floatline and one pinger every 91 m along the leadline offset midway between the pingers on the floatline. A typical net of 1,830 m would therefore require 21 pingers along the floatline and 20 pingers along the leadline. The actual number and configuration of pingers varied due to differences in net length, pinger failures, and other uncontrolled factors (see below).

The experiment started at the beginning of the swordfish season in August 1996 and continued until the end of October 1997 when pingers became mandatory in this fishery. Based on previously measured rates of cetacean entanglement in this fishery, an *a priori* power analysis[10] indicated that approximately 1,100 sets would be needed (550 with pingers and 550 without) to obtain a 90% probability of detecting a 50% decline in overall cetacean mortality (based on a Fisher exact test with $\alpha = 0.10$, 1-tailed). A multiyear experiment was anticipated, but with only 420 observed sets in 1996, the overall change in cetacean entanglement (a 77% reduction) was statistically significant.[11] Based on these preliminary results, pingers were made mandatory on 28 October 1997 *via* Federal regulations under the authority of the U.S. Marine Mammal Protection Act, effectively ending the controlled experiment.

Data Collection

Observers on fishing vessels collected data on net specification (including number of pingers used), environmental conditions at the beginning and end of the set, vessel activities during the set, and location at the beginning of the set (Table 1). During net retrieval, the observer was stationed in a good position to observe the retrieval and recorded numbers and species of marine mammals (Table 2), sea birds, turtles, and fish caught. Data were checked by observers in the field and when they entered their data using a range-checking data entry program. Computer files were also checked for outliers, missing fields, and inconsistencies using an edit

[7] The use of brand names does not imply endorsement by the National Marine Fisheries Service.

[8] Unpublished data from K. C. Baldwin, C. Pacheco, and S. D. Kraus, Center for Ocean Engineering, University of New Hampshire, Durham, NH 03824, U.S.A.

[9] Unpublished data from D. Norris, Biomon, 718 C West Victoria Street, Santa Barbara, CA 93101, U.S.A.

[10] Barlow, J. 1996. Design of an experiment to test the effectiveness of "pingers" to reduce marine mammal by-catch in the west-coast drift gillnet fishery for swordfish and sharks. Unpublished report. 8 pp. Available from the Southwest Fisheries Science Center, 8604 La Jolla Shores Drive, La Jolla, CA 92037, U.S.A.

[11] Julian, F. 1997. Cetacean mortality in California gill net fisheries: preliminary estimates for 1996. Paper SC/49/SM2 (unpublished). 13 pp. Available from the International Whaling Commission, The Red House, Station Road, Histon, Cambridge CB4 4NP, United Kingdom.

Table 1. Descriptions of variables used in analyses. Variable types coded: cat = categorical, cnt = continuous, ord = ordinal, inv = interval. Range of continuous variable or categories of categorical variable given under "Values." Mean statistics consist of arithmetic mean for continuous and interval variables and odds of "1" for binary categorical variables. "×" indicates tests performed on each variable. "Entangle" indicates Wilcoxon tests of variable for difference in entanglement rate. "Pings" indicates Wilcoxon test for differences in variable between sets with and without pingers (check on randomization). "GLM" indicate variable included in the Generalized Linear Model analyses.

				Mean statistics			Tests		
Variable name	Description	Type	Values	All sets	With pingers	Without pingers	Entangle	Pings	GLM
Controllable mechanical variables									
dlight	deck lights on at night? (1 = on)	ord	{0, 1}	0.74	0.75	0.76	×	×	×
engine	engine on at night? (1 = on)	ord	{0, 1}	0.08	0.04	0.12	×	×	×
gener	generator on at night? (1 = on)	ord	{0, 1}	0.83	0.83	0.82	×	×	×
sticks	number of light sticks deployed	cnt	[0, 40]	4.9	4.4	5.4		×	×
sticks present	light sticks deployed? (1 = deployed)	ord	{0, 1}	0.42	0.38	0.46	×	×	×
pings	number of pingers deployed	cnt	[0, 45]	17	32	0			×
pings present	pingers deployed? (1 = deployed)	ord	{0, 1}	0.48	1.0	0.0	×		×
soak	number of hours net submerged	cnt	[0, 62]	12.5	12.7	12.3		×	×
soak lo/hi	0 = (soak ≤ 12 h) 1 = (soak > 12 h)	ord	{0, 1}	0.51	0.53	0.48	×	×	×
sonar	sonar on at night? (1 = on)	ord	{0, 1}	0.14	0.13	0.15	×	×	×

Table 1. Continued.

Variable name	Description	Type	Values	Mean statistics: All sets	Mean statistics: With pingers	Mean statistics: Without pingers	Tests: Entangle	Tests: Pings	Tests: GLM
Environment variables									
bcld	cloud cover at start of set: linear scale 0 = 0%, 8 = 100%, 9 = too dark	inv	{0, 1,. . .,9}	3.73	3.61	3.85		×	
bcld lo/hi	0 = clear (bcld < 5) 1 = cloudy (bcld ⩾ 5)	ord	{0, 1}	0.36	0.35	0.36	×	×	×
ecld	cloud cover at end of set: linear scale 0 = 0%, 8 = 100%, 9 = too dark	inv	{0,. . .,9}	5.2	5.1	5.3		×	
ecld lo/hi	0 = clear (ecld < 5) 1 = cloudy (ecld ⩾ 5)	ord	{0, 1}	0.30	0.31	0.30	×	×	×
bbeau lo/hi	Beaufort sea state at start of set 0 = calm (<3), 1 = rough (⩾3)	ord	{0, 1}	0.49	0.49	0.48	×	×	×
ebeau lo/hi	Beaufort sea state at end of set 0 = calm (<3), 1 = rough (⩾3)	ord	{0, 1}	0.44	0.45	0.43	×	×	×
season	0 = May–Oct, 1 = Nov–Apr	cat	{0, 1}	0.56	0.55	0.56	×	×	×
depth	Water depth at time of net retrieval (fathoms)	cnt	[0, 2,700]	1,150	1,167	1,135		×	×
depth lo/hi	0 = shallow (<1,000 fathoms) 1 = deep (>1,000 fathoms)	ord	{0, 1}	0.46	0.48	0.44	×	×	×
Net variables									
extend lo/hi	0 = (extend <37 ft) 1 = (extend ⩾ 37 ft)	cat	{0, 1}	0.25	0.27	0.24	×	×	×

Table 1. Continued.

Variable name	Description	Type	Values	Mean statistics			Tests		
				All sets	With pingers	Without pingers	Entangle	Pings	GLM
extend	distance between cork line and surface floats (ft)	cnt	[12, 78]	38.2	37.3	38.2		×	×
mesh	stretched mesh size (in.)	cnt	[15, 22]	20.3	20.4	20.3		×	×
mesh lo/hi	0 = (mesh $\leqslant$20) 1 = (mesh >20)	ord	{0, 1}	0.51	0.51	0.50	×	×	×
ntcolor	color of net	cat	{green, red, blue, brown, other}	222, 24, 4, 64, 30	109, 13, 2, 31, 11	113, 11, 2, 33, 19	×		
netdpth	number of meshes, corkline to leadline	cnt	[36, 1,050]	128.5	128.2	128.8		×	×
netlen	length of net (fathoms)	cnt	[222, 1,000]	950.7	949.3	951.7		×	×
slack	percent slack: calculated from number meshes hanging and hanging length	cnt	[0, 50]	42.1	42.2	42		×	×
Location/season variables									
region	0 = south of 34.5°N, 1 = north of 34.5°N	cat	{0, 1}	0.45	0.46	0.44	×	×	×
lat	latitude at start of set	cnt	[30, 47]	34.79	34.87	34.71		×	
long	longitude at start of set	cnt	[117, 126]	120.6	120.9	120.4		×	

Table 1. Continued.

				Mean statistics			Tests		
Variable name	Description	Type	Values	All sets	With pingers	Without pingers	Entangle	Pings	GLM
area	Five fishing regions. Regions 1, 3, 4, 5 separated by latitudes 33.83°, 34.33°, and 42.00°N. Region 2 composed of small disjoint areas surrounding Channel Islands.	cat	{1,..., 5}	315, 13, 7, 253, 21	161, 10, 5, 128, 10	154, 3, 2, 125, 11			
month	month of set	cat	{1,..., 12}	69, 0, 0, 0, 0, 0, 0, 54, 133, 157, 103, 93	36, 0, 0, 0, 0, 0, 0, 26, 66, 90, 48, 48	33, 0, 0, 0, 0, 0, 0, 28, 67, 67, 55, 45			×

Table 2. Frequency distribution of net entanglements by species for all sets, for sets with pingers, and for sets without pingers.

Species	All sets	Sets with pingers (n = 295)				Sets without pingers (n = 314)			
		# of Entanglements per set				# of Entanglements per set			
		1	2	3	Total	1	2	3	Total
Common dolphin, short-beaked *Delphinus delphis*	24	3			3	17	2		21
Common dolphin, long-beaked *Delphinus capensis*	1				0	1			1
Northern right whale dolphin *Lissodelphis borealis*	8			1	3	5			5
Pacific white-sided dolphin *Lagenorhynchus obliquidens*	4	1			1	1	1		3
Risso's dolphin *Grampus griseus*	1	1			1				0
Dall's porpoise *Phocoenoides dalli*	3	1			1	2			2
Short-finned pilot whale *Globicephala macrorhynchus*	1				0	1			1
Sperm whale *Physeter macrocephalus*	1	1			1				0
"Other cetaceans" (excluding short-beaked common dolphin)	19	4	0	1	7	10	1	0	12
All cetaceans	43	7	0	1	10	27	3	0	33
Northern elephant seal *Mirounga angustirostris*	13	3			3	10			10
California sea lion *Zalophus californianus*	18	4			4	14			14
All pinnipeds	31	7	0	0	7	24	0	0	24

program. Observers opportunistically recorded data on marine mammal sightings during the day as the vessel traveled from one location to another.

Data Selection

Experimental protocols were not followed on every set. Sometimes skippers chose not to employ pingers in rough seas (18 cases), during the first set of a season or the first set with an inexperienced crew (7 cases), when pingers were causing problems (2 cases), or for other reasons (20 cases). Occasionally, skippers chose to employ pingers even when the protocol called for none (because marine mammals were known to be present, 5 cases). For analyses presented here, we excluded every set which did not follow the experimental protocols. To prevent experimental manipulation of results, we also excluded all the sets from trips that were judged to be substantially out of compliance with experimental protocols (more than one-third of sets not following protocols). Of the 713 sets that were observed during the experiment, 104 were excluded, resulting in 609 sets that we included in our analyses.

Statistical Analyses

Descriptions and summary statistics for variables that are likely to affect marine mammal entanglement are given in Table 1. We use abbreviated variable names (Table 1) throughout this report. Some continuous variables and categorical variables with multiple states were collapsed to two-state categorical variables for some analyses; for example, the number of chemical light sticks ("sticks") was included as a continuous variable and as the categorical variable "sticks present."

The random distribution of net and set variables in pingered and unpingered sets was tested using the two-sample Wilcoxon rank sum test (two-tailed). The reduction in marine mammal bycatch when pingers were present was tested using a one-tailed Fisher's exact test using a 2×2 contingency table (no entanglements *vs.* one or more entanglements per set). Reduction in the number of entanglements per set was tested with a non-parametric Wilcoxon rank sum test (one-tailed test). The distributions of fish catch were far from Poisson or normal; therefore, the reduction in the number of target and non-target fish caught was tested only with the Wilcoxon rank sum test (one-tailed).

Multivariate tests of the effect of pingers and other variables on marine mammal entanglement were conducted using a Generalized Linear Modelling (GLM) framework (McCullagh and Nelder 1989). A logarithmic link function was used to approximate a Poisson error structure:

$$\ln(E[Y_i]) = \beta_0 + \sum X_{ij}\beta_j$$

where Y_i is the number of entanglements for observation i, (for a species or species group); X_{ij} is the value of predictor variable j for observation i, which may include main effects and interaction terms; β_j is the model coefficient for predictor variable j; and β_0 is the coefficient for a constant term. The error structure was actually allowed to vary as

$$\text{var}(Y_i) = \sigma^2 E[Y_i]$$

where the dispersion parameter, σ^2, can be estimated from the residuals to accommodate deviations from Poisson expectations ($\sigma^2 = 1.0$). Maximum likelihood estimates of the coefficients, β_j, were computed using iteratively reweighted least squares using SPLUS software. According to likelihood theory, these parameters are asymptotically normal for known variance, hence, a t-test was used to determine whether an estimated coefficient is significantly different from zero.

Three pinger response variables (entanglements of "short-beaked common dolphin," "other cetaceans," and "pinnipeds") were modeled as linear functions of predictor variables including the number of pingers ("pings"), the number of pingers squared ("pings squared"), and each variable indicated under the "GLM" column of Table 1. A "net volume" term, the product of soak time, net length, and net depth, was included by adding soak time, net length, and net depth simultaneously in a single model. Preliminary multivariate models were built using an approximate stepwise approach implemented in SPLUS. These models were then pruned by sequentially removing the least significant variable until all remaining variables were statistically significant using a test for a reduction in overall deviance ($\alpha = 0.05$). For Poisson-distributed entanglements, a chi-square test was used for model selection, and for over-dispersed models, an F-test was used (McCullagh and Nelder 1989).

Results

Entanglements

A total of 74 marine mammals (43 cetaceans and 31 pinnipeds) was entangled in the 609 sets during the experiment (Table 2). Short-beaked common dolphins were the most common species and accounted for over half of the cetacean entanglements. Pinniped entanglements included northern elephant seals (*Mirounga angustirostris*) and California sea lions (*Zalophus californianus*) in roughly equal numbers. For both cetaceans and pinnipeds, entanglement rates in nets with pingers were approximately one-third the rates in nets without pingers (Table 3).

Most marine mammal entanglements consisted of single individuals; however, three northern right whale dolphins (*Lissodelphis borealis*) were found entangled in a single net (with 24 pingers). The empirical distributions of the number of entanglements per set for "short-beaked common dolphins," "other cetaceans," and "pinnipeds" did not differ significantly from the Poisson distribution (chi-square goodness of fit, $\alpha = 0.05$).

Possible Confounding Factors

There were no significant differences between pingered and unpingered nets for any of the variables tested except for the number of light sticks ("sticks" and "sticks present"). Geographic distributions of sets showed no obvious differences between pingered and unpingered sets (Fig. 1). Only two variables other than the number of pingers were related to entanglement rates. Entanglement of short-beaked common dolphins was significantly related to the number of common dolphins sightings on that trip ("cdsight," Wilcoxon rank sum test, $P = 0.0008$). Entanglement of "other cetaceans" was not significantly related to any other variables. Entanglement of pinnipeds was significantly related to the cloud cover at the end of the set ("ecld lo/hi," Wilcoxon rank sum test, $P = 0.04$). Using a Bonferroni correction for multiple

Table 3. Bycatch rates and one-tailed statistical tests of decreases in entanglements in sets with pingers compared to sets without pingers.

	Bycatch rates (total bycatch/total sets)		Statistical test results (P-value)	
Species	Sets with pingers	Sets without pingers	Wilcoxon rank sum test	Fisher's exact test
Common dolphin, short-beaked *Delphinus delphis*	0.010	0.067	0.001	0.001
Common dolphin, long-beaked *Delphinus capensis*	0.000	0.006	0.227	0.258
Northern right whale dolphin *Lissodelphis borealis*	0.010	0.016	0.070	0.124
Pacific white-sided dolphin *Lagenorhynchus obliquidens*	0.003	0.010	0.317	0.329
Risso's dolphin *Grampus griseus*	0.003	0.000	0.789	0.485
Dall's porpoise *Phocoenoides dalli*	0.003	0.006	0.318	0.330
Short-finned pilot whale *Globicephala macrorhynchus*	0.000	0.003	0.227	0.258
Sperm whale *Physeter macrocephalus*	0.003	0.000	0.227	0.485
"Other cetaceans" (excluding short-beaked common dolphin)	0.024	0.041	0.087	0.127
All cetaceans	0.034	0.110	<0.001	<0.001
Northern elephant seal *Mirounga angustirostris*	0.0100	0.032	0.036	0.056
California sea lion *Zalophus californianus*	0.014	0.045	0.013	0.020
All pinnipeds	0.022	0.076	0.003	0.003

testing ($\alpha = 0.05/19 = 0.002$), only one variable (the number of common dolphin sightings) remained significantly related to entanglements.

Pinger Effects on Entanglements of Short-beaked Common Dolphins

The bycatch of short-beaked common dolphins was significantly lower in nets with pingers ($P = 0.001$, for both the one-tailed Wilcoxon rank sum test and the Fisher exact test, Table 3). The only other variable that appeared to be statistically significant was the number of common dolphin sightings on a trip ($P < 0.001$). The only variable selected in the stepwise log-linear model was the number of pingers squared ($P = 0.0001$, Table 4, Fig. 2).

Pinger Effects on Entanglements of Other Cetaceans

The bycatch of "other cetaceans" (other than short-beaked common dolphins) was not significantly related to pinger use in univariate tests ($P = 0.08$ and $P = 0.13$ using the one-tailed Wilcoxon rank sum test and the Fisher exact test, respectively) (Table 3). However, when the number of pingers used was included in a GLM model (as number of pingers squared), the pinger effect was statistically significant ($P = 0.03$, Table 4, Fig. 3). The only other significant variable in the GLM model was the Beaufort sea state at the end of the set. Pingers were not significantly related to entanglement rates for any of the other species tested separately, but sample sizes were low in all cases (only one to eight total entanglements per species). Entanglement rates were lower in pingered nets for five out of the seven other cetacean species.

Pinger Effects on Entanglements of Pinnipeds

Pinniped bycatch was also significantly lower in pingered nets ($P = 0.003$ or 0.003, one-tailed Wilcoxon rank sum test or the Fisher exact test, respectively) (Table 3). For individual species tested alone, bycatch reduction was significant for California sea lions ($P = 0.01$ or 0.02, respectively) and marginally significant for northern elephant seals ($P = 0.04$ or 0.06, respectively). The number of pingers ("pings") was one of four significant variables selected in the stepwise building of a GLM model for pinniped entanglement ($P = 0.007$, Table 4, Fig. 4). The other significant variables in the GLM model were water "depth," "gener," and "engine." In univariate tests the only significant variable in explaining pinniped entanglement was cloud cover ("ecldlohi"). This variable is not correlated with pinger use and cannot be used to explain the effect of pingers on entanglement.

Pinger Effects on Catch

There were no significant differences in the catch rates for the three target fish species (broadbill swordfish, common thresher shark, and shortfin mako shark) (one-tailed Wilcoxon rank sum test, Table 5). The catch rates of the non-target fish species were also not significantly related to pinger use (Table 5).

Discussion

Pingers significantly reduced total cetacean and pinniped entanglement in drift gill nets without significantly affecting swordfish or shark catch. Results also

Table 4. Analysis of deviance tables for log-linear fits to marine mammal entanglements. Initial models built using approximate stepwise approach implemented in SPLUS, then non-significant variables deleted (sequentially removing least significant) until remaining terms all statistically significant ($\alpha = 0.05$). *P*-value is significance level from either chi-square test or (for "other cetaceans") approximate *F*-test for change in deviance.

Model	Residual deviance	Degrees of freedom	Change in deviance	*P*	Estimated coefficient	Standard error of coefficient
Common dolphin (short-beaked) entanglement model (estimated dispersion = 1.01)						
Grand mean	160.77	608			−2.721	0.217
+ Pings^2	142.74	607	−15.03	0.0001	−0.0016	0.0006
"Other cetaceans" entanglement model (estimated dispersion = 1.26)						
Grand mean	141.12	608			−3.654	0.296
+ Pings^2	135.43	607	−5.694	0.03	−0.0009	0.0005
+ ebeaulohi	130.74	606	−4.690	0.05	1.023	0.555
Pinniped entanglement model (estimated dispersion = 1.01)						
Grand mean	187.40	607			−2.830	0.206
+ Depth	182.46	606	−4.94	0.03	−0.00065	0.00026
+ Pings	175.15	605	−7.31	0.007	−0.031	0.011
+ Gener	170.70	604	−4.45	0.03	1.090	0.694
+ Engine	165.87	603	−4.83	0.03	−6.730	10.35

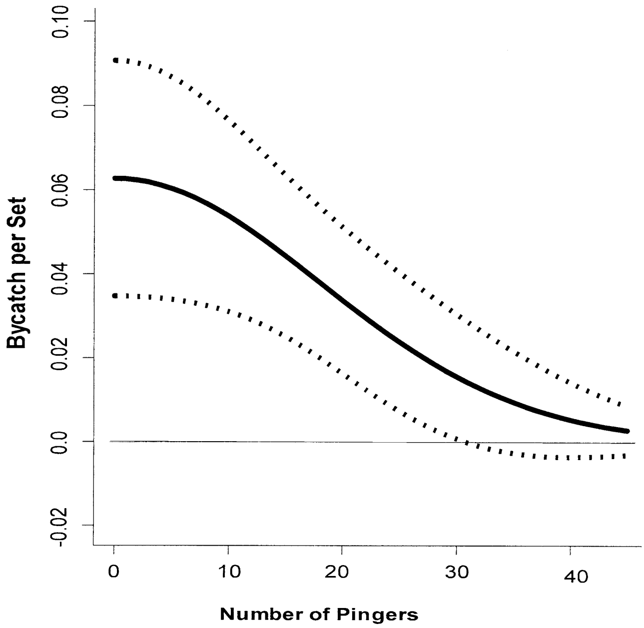

Figure 2. Predicted bycatch per set of short-beaked common dolphins as function of number of pingers based on GLM. Dotted lines show approximate 95% confidence intervals.

indicate a greater reduction with a greater number of pingers. These results are similar to results of previous experiments that showed a significant reduction in harbor porpoise bycatch when pingers were used on set gill nets (Kraus *et al.* 1997, Larsen[2], Trippel 1999, Gearin *et al.* 2000). Our experiment is, however, the first unequivocal demonstration that pingers are correlated with a significant reduction in the bycatch for a delphinid cetacean (short-beaked common dolphin) and for a pinniped (California sea lion). The significant reduction in total cetacean bycatch was largely driven by the reduction in bycatch of short-beaked common dolphins. Bycatch reduction was not statistically significant for any other cetacean species (although, bycatch was lower for most). An impractically large sample would be required to find a statistically significant result for rare species, even if their response was the same as for common dolphins.

Because of the potential importance of these results in reducing marine mammal bycatch worldwide, it is important to investigate potential spurious causes of these patterns. One potential concern is the lack of a true double-blind control in our experimental protocol. We cannot tell whether the observed pinger effect was caused by the sound produced by the pingers or by the presence of something novel hanging from the net. We believe that the visual enhancement caused by the presence of the pingers at night is trivial and that the sounds they emit almost certainly caused the reduction in bycatch; however, our design does not allow us to distinguish between these hypotheses. A more serious concern is the possible direct or inadvertent manipulation of the results by the observers or the fishermen. The observers had no direct role in the design or analysis of the experiment and would not directly benefit by manipulating the results (other than the common human

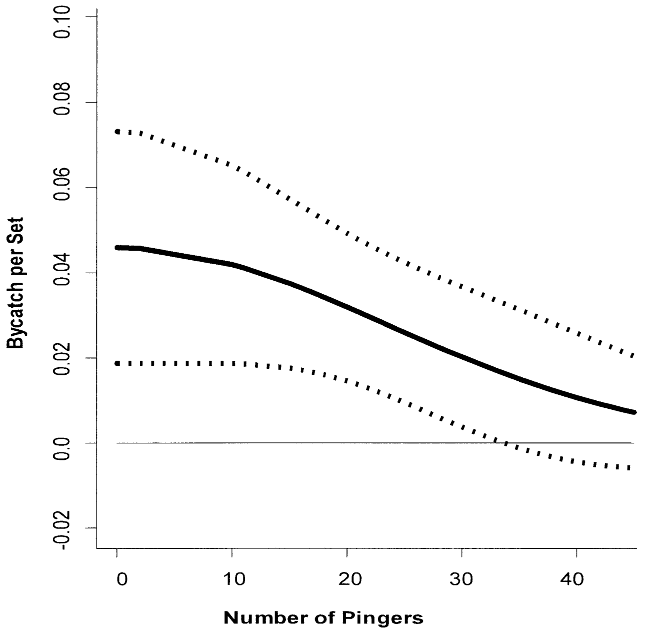

Figure 3. Predicted bycatch per set of "other cetaceans" (other than short-beaked common dolphins) as function of number of pingers based on GLM. Dotted lines show approximate 95% confidence intervals.

desire for successful outcomes). Fishermen knew that their industry was under growing scrutiny and that, if bycatch were not reduced, they might face additional regulations or even closure; therefore, fishermen had a strong incentive to show that pingers worked. The ability for fishermen to manipulate results was limited because the fishermen had already chosen a location before a set was determined to be "pingered" or "unpingered." Sets were eliminated from analysis when this protocol was not followed. Once a net is set in a given location, there is little that a fisherman can do to affect marine mammal bycatch. Of the variables that are under a captain's control ("dlight," "engine," "gener," "sticks," "soak," and "sonar"), only "sticks" was significantly correlated with pinger use, and none were significantly correlated with cetacean bycatch. The effect of pingers on bycatch was greater than the effects of any other variables (except number of common dolphin sightings), and it would be impossible to contrive such a strong pinger effect by subtle experimental manipulations. Additional analyses (including classification and regression trees, CART) were conducted to look for other variables that might explain patterns of entanglements,[12] and pingers also emerged as an important explanatory variable in those studies.

[12] Cameron, G. 1999. Report on the effect of acoustic warning devices (pingers) on cetacean and pinniped bycatch in the California drift gillnet fishery. Administrative Report LJ-99-08C (unpublished). 71 pp. Available from the Southwest Fisheries Science Center, 8604 La Jolla Shores Drive, La Jolla, CA 92037, U.S.A.

Table 5. Catch (number of fish) and one-tailed statistical tests for decreases in catch rates for sets with and without pingers.

Species	Total catch (# of fish)	Sets with pingers		Sets without pingers		Wilcoxon rank sum
		Catch	Catch/set	Catch	Catch/set	*P*-value
Target						
Swordfish, broadbill *Xiphias gladius*	1,075	513	1.74	562	1.79	0.46
Shark, Common thresher *Alopius vulpinas*	462	170	0.58	292	0.93	0.24
Shark, mako *Isurus oxyrinchus*	815	418	1.42	397	1.26	0.53
Non-target						
Mola, common *Mola mola*	2,162	1,012	3.43	1,150	3.66	0.43
Opah *Lampris guttatus*	607	306	1.04	301	0.96	0.30
Shark, bigeye thresher *Alopius supersiliosus*	69	25	0.09	44	0.14	0.32
Shark, blue *Prionace glauca*	2,119	1,066	3.61	1,053	3.35	0.71
Tuna, albacore *Thunnus alalunga*	1,117	696	2.36	421	1.34	0.46
Tuna, bluefin *Thunnus thynnus*	572	295	1.00	277	0.88	0.37
Tuna, skipjack *Katsuwonus pelamis*	580	274	0.93	306	0.97	0.32

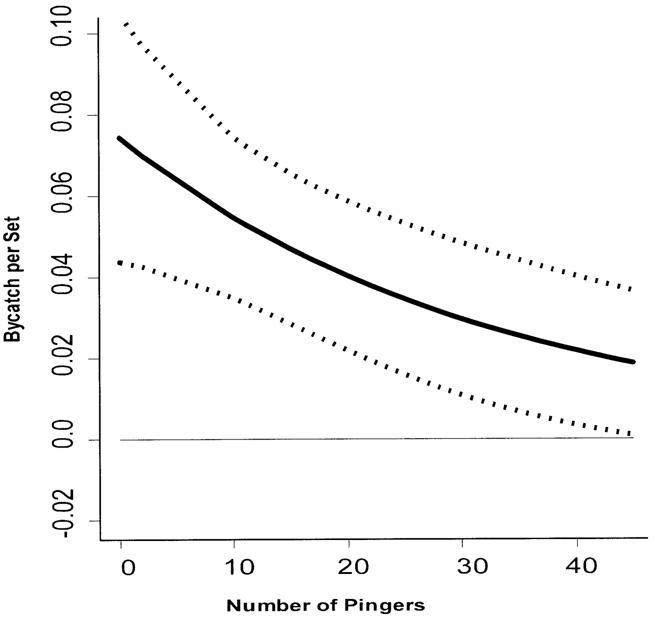

Figure 4. Predicted bycatch per set of pinnipeds as function of number of pingers based on GLM. Dotted lines show approximate 95% confidence intervals.

Additional work is needed to determine the optimal number and placement of pingers on drift gill nets. Log-linear models indicate that mortality rate is still decreasing with number of pingers within the range of 30–40 pingers (Fig. 2–4); however, there were few data during this experiment within the range of 1–20 pingers, so there is considerable uncertainty about the shape of this response curve in that region. The GLM model identified Beaufort sea state, engine noise, and generator noise as possible explanatory variables in some analyses. All three variables are sources of noise that might mask the sounds produced by pingers; however, engine and generator noise could also act to alert animals to the presence of the net. Water depth is another explanatory variable for pinnipeds; this might be expected because California sea lions forage only in the shallower, inshore portion of the operational range of drift gill net vessels.

The reduction we see in pinniped entanglements is particularly surprising because others have predicted that pinnipeds might be attracted to nets to feed on the captured fish (the "dinner bell" effect). However, in an experimental study of the response of captive California sea lions to pingers, Anderson (2000) showed that they initially responded with a start followed by avoidance (five of six sea lions left the water). This response helps explain the reduction we noted in sea lion entanglements.

Although pingers appear to reduce bycatch for a large range of marine mammal species, we echo the concerns that have been expressed by many other authors that animals may habituate to pingers. Given the relatively small number of nets and the huge area fished, habituation may be less of a concern for the California drift gill net fishery than for intensive, localized set gill net fisheries in the Gulf of Maine and in the North Sea. We believe that pingers are unlikely to reduce the bycatch of all cetacean species or all pinniped species.

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